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LASER PEENING OF DOVETAIL SLOTS BY FIBER  
OPTIC AND ARTICULATE ARM BEAM DELIVERY

PRIORITY DATA

This application hereby claims the benefit under Title 35,  
United States Codes § 119(e) of any United States application serial  
no. 60/449,565 filed February 21, 2003, and is hereby incorporated  
by reference.

5                                   BACKGROUND OF THE INVENTION

1.   Field of the invention.

The present invention relates to a method of laser peening a  
hidden surface of a workpiece, the hidden surface not being  
line-of-sight accessible to a laser beam for treatment, and, more  
10 particularly, to a method of laser peening dovetail slots in turbo  
machinery.

2.   Description of the related art.

In two components such as dovetail slots in turbo machinery,  
a significant cause of fatigue damage and failure in such components  
15 originates at the contact points therebetween. These contact points  
can be high stress, high fretting areas. As a result, fatigue cracks  
tend to initiate in such areas and can eventually propagate to an  
unacceptable damage threshold or failure.

Fretting fatigue is a process that occurs when two or more metallic components are in intimate contact with each other under active loading conditions. It occurs as a result of major axial load between two components accompanied by a cyclic load that  
5 introduces a small relative motion between the two components, such motion being on the order of microns. The fretting fatigue cracks tend to initiate in an area where the relative motion is greatest between the two surfaces. This area is typically at the edges of the contact area therebetween. Cracks generated from the cyclic  
10 load propagate in a direction at about  $45^\circ$  of the surface to the two components, due to the shear stress generated from the relative movement therebetween. The magnitude of this surface contact shear stress decreases with depth below the surface. Therefore, as the crack propagate into the component, the shear stress decreases until  
15 the cracks reach a depth at which the global stress begins to dominate.

When the global stress begins to dominate, the cracks begin to propagate perpendicular to the principal global tensile stress component. The crack can continue to propagate under the influence of the global tensile stress, possibly leading to eventual component  
20 failure.

Fretting fatigue is a relatively common problem in a number of components where there is a high contact stress between contact surfaces and vibratory stress that produces a slight relative motion

between the two surfaces. Fretting fatigue often occurs at dovetail surfaces on mating turbine disk and blade attachment surfaces in aircraft jet engines. In the engines, centrifugal forces pull the blades against the surfaces of the dovetail slots of a turbine disk.

5 This global loading is accompanied by a vibratory stress source that causes slight movement of the blade dovetail surfaces against the dovetail slot surfaces as the disk rotates. This movement can result in fretting and may lead to fretting crack initiation and, potentially, fatigue-induced failures of the disks and/or blades.

10 As such, limiting or reducing the propagation of shear cracking caused by fretting fatigue can decrease maintenance costs and increase the life of a component.

One of the current measures taken to alleviate the fretting fatigue problem on dovetail slots has been the application of soft, compliant metallic coatings, such a copper-nickel-indium coatings, on the blade attachments. The soft, compliant coatings are applied as a thin layer to the blade attachment surface. Such coatings allow the peak contact stresses to be distributed uniformly across the contact area and reduce the relative motion between the surfaces.

20 While these measures have helped extend service life, such coating have their own associated problems. These coatings generally degrade with each coating cycle and have to be reapplied to the attachment surfaces at periodic maintenance intervals.

Another technique that potentially increases fretting fatigue resistance is shot peening. However, two aspects limit shot peening as a method to increase fretting fatigue resistance in dovetail slots.

The first limitation is that shot peening is only able to develop  
5 compressive residual stresses to relatively shallow depths. The compressive stress is limited to approximately 0.1 mm under typical processing conditions, where the shot media strike the surface at a near normal angle to the surface. However, the fretting fatigue cracks that are typically generated can be as deep as 0.1 mm and  
10 thus breach the residual compressive stress layer created by shock peening.

The second limitation associated with shot peening dovetail shock surfaces is the tight confines of the dovetail slot. The surfaces of the dovetail disk slots are difficult to access, thereby  
15 preventing a typical application of the shot peening process. In the tight confinement of the dovetail slot, the surfaces have to be shot peened at a lower incident angle, resulting in a lessened efficiency of the shot peening. Lowering the incident angle reduces the effective depth of the compressive stress layer created since  
20 the normal force (i.e., the force component perpendicular to the treated surface) of the shot media striking the surface is reduced significantly.

Laser peening processing of the fretting-prone areas on the dovetail slots of the disks is an excellent candidate technology to solve the fretting fatigue problem. Laser peening processing is capable of imparting deep residual compressive stresses (up to 5 1 mm deep) into the treated surface. The laser peening process can be applied at almost any angle to the surface as long as there is line-of-sight access to the surface to be processed. The surfaces can be processed with a low incident angle laser beam, if necessary, because the shockwave produced will propagate normal to the surface 10 regardless of the laser beam incident angle.

Typical laser shock processing techniques and equipment can be found in U.S. Patent No. 5,131,957 to Epstein along with that of U.S. Patent No. 5,741,559 to Dulaney, each commonly assigned to the assignee of the present invention, the content of both of which 15 is hereby incorporated by reference. U.S. Patent No. 6,469,275 to Dulaney et al, which is commonly assigned along with the present invention and hereby incorporated by reference, discloses the use of laser peening to treat both the internal and external sections of a dovetail section (e.g., Figs. 9 and 10 thereof).

20 Despite the significant potential offered by the laser peening processing to solve the fretting fatigue problem in dovetail slots, the immediate use of laser peening for treating the fretting surfaces

has been inhibited because a portion of the dovetail surface has not been directly accessible with the laser beam.

What is needed is the art is the development of new, innovative beam delivery concepts that will promote delivery of laser peening energy to all surfaces, including those previously considered "hidden", to permit producing compressive residual stresses into these surfaces via laser peening.

#### SUMMARY OF THE INVENTION

The present invention relates to a selectively positionable laser peening apparatus and a method of use therefor, the selectively positionable laser peening apparatus having a laser transmission end, the laser transmission end being variably and selectively positionable and thereby configured for variably and selectively directing laser energy upon a hidden surface of a workpiece.

The present invention, in another form thereof, comprises a method of laser peening a laser surface of a workpiece, the hidden surface not being line-of-sight accessible to a laser beam for treatment. In the first step of the method, a selectively positionable laser peening apparatus is provided. The selectively positionable laser peening apparatus has a laser transmission end, the laser transmission end being variably and selectively positionable and thereby configured for variably and selectively directing laser energy upon the hidden surface. The next step is

that of directing the laser transmission end toward the hidden surface.

Finally, laser energy is delivered via the laser transmission upon the hidden surface to thereby initiate laser peening thereof.

The present invention, in yet another form thereof, comprises  
5 a laser peening apparatus for laser peening a hidden surface of a workpiece, the hidden surface not being line-of-sight accessible to laser energy of treatment thereof. The apparatus includes a pulsed laser system and a laser directing unit. The pulse laser system is configured for generating the laser energy used for laser peening.

10 The laser directing unit operatively receives and channels the laser energy generated by the pulsed laser system. The laser directing unit includes a laser transmission end, the laser directing unit being capable of variably and selectively positioning that laser transmission end. The laser directing unit is thereby configured  
15 for variably and selectively directing laser energy upon the hidden surface via the laser transmission end. The laser directing unit includes one of a fiber-optic laser delivery mechanism and a telescopic articulated arm mechanism.

An advantage of the present invention is that it facilitates  
20 the delivery of laser energy to "hidden" workpiece surfaces, such as dovetail surfaces, to thereby permit such surfaces to attain compressive residual stresses using laser peening.

Another advantage of the present invention through use of the apparatus of the present invention, laser energy can be delivered at almost any angle and at any position of the surface of the workpiece, even to surfaces previously considered to be hidden.

5 Yet another advantage of the present invention is that the laser peening process only needs to be performed once to a given surface.

The surface does not need to be reprocessed through its surface life, since the compressive stresses developed during laser peening are maintained through the life of the component. That the process  
10 only need be preformed once greatly reduces maintenance costs.

Yet another advantage of the present invention is that it can potentially be applied to obtain compressive residual stresses inside holes with high aspect ratios, holes where compressive residual stresses are needed to increased fatigue life, and/or any parts that  
15 have surfaces that need peening but are not directly accessible with current laser beam delivery techniques. As such, this technique is potentially useful in the processing of components in areas such as automotive, machine tools, mass production equipment, and aerospace.

#### BRIEF DESCRIPTION OF THE DRAWINGS

20 The above-mentioned and other features and advantages of this invention, and the manner of attaining them, will become more apparent and the invention will be better understood by reference to the



following description of various embodiments of the invention taken in conjunction with the accompanying drawings, wherein:

Figs. 1-4 are side, schematic views of four separate embodiments of the laser peening apparatus of the present invention, each  
5 employing a particular fiber optic beam delivery system as the laser directing unit;

Fig. 5 is a side, schematic view of an embodiment of the laser peening apparatus of the present invention, employing a telescopic articulated arm mechanism as the laser directing unit; and

10 Fig. 6 is a cross-sectional, schematic view of an adjustable telescoping member of the telescopic articulate arm mechanism shown in Fig. 5, the adjustable telescoping member being shown positioned within a dovetail slot of a blade attachment.

Corresponding reference characters indicate corresponding  
15 parts throughout the several views. The exemplifications set out herein illustrate at least one preferred embodiment of the invention, in one form, and such exemplifications are not to be construed as limiting the scope of the invention in any manner.

#### DETAILED DESCRIPTION OF THE INVENTION

20 The present invention relates to a laser peening apparatus 10 (various embodiments of which are shown in Figs. 1-6) that is capable of laser peening surfaces that are not line-of-sight accessible to

the laser beam. Laser peening apparatus 10 generally includes a pulsed laser system 12 and a laser directing unit 14.

Pulsed laser system 12 includes one or more laser units 16.

Each laser unit 16 has an active medium fabricated from

5 Nd-doped-phosphate glass, YAG, or YLF. The pulse width of each laser unit is advantageously less than 50 ns, and its operational frequency is advantageously greater than 1 Hz. The laser intensity to be generated on the surface being treated is preferably greater than 4 GW/cm<sup>2</sup>, and the beam diameter generated by such a laser unit 16  
10 on the surface of workpiece may be less than 2 mm.

Figs. 1-4 show various embodiments of laser peening apparatus 10 which specifically employ a fiber optic beam delivery system 14a as the laser directing unit 14. Each laser directing unit 14 of the embodiment shown in Figs. 1-4 has at least one fiber optic cable  
15 18, an input focusing lens 20 associated with each fiber optic cable 18, and a single output focusing lens 22 for the fiber optic beam delivery system 14a.

Each fiber optic cable 18 used for fiber optic beam delivery system 14a is to be formed of a flexible fiber allowing the direction  
20 of a laser beam carried therewithin to be redirected toward a surface that is not in line-in-sight of the overall system. The fiber optic cable 18 used for the beam delivery will preferably have an inside

core diameter of greater than 500 microns, the core of which can be either hollow or solid.

Each input focusing lens 20 is arranged and configured for focusing and thereby directing laser energy into a corresponding fiber optic cable 18. Output focusing lens 22 is located at a laser transmission end 24 of the laser directing unit 14, in this case specifically fiber optic beam delivery system 14a. Output focusing lens 22 is thereby positioned and configured for controlling the size of beam on a target surface. Depending on the overall configuration of the laser directing unit and whether the overall laser peening apparatus 10 incorporates a water flow therewithin, output focusing lens 22 may also act as a window to prevent water from flowing into laser directing unit 14. Four separate embodiments of fiber optic beam delivery system 14a are shown in Figs. 1-4, respectively.

Fig. 1 shows a laser beam from a pulsed laser system 12 being coupled into a single fiber optic cable 18. The output from fiber optic cable 18 is then coupled to the surface of a given target by output focusing lens 22 at laser transmission end 24. The flexible fiber 18 allows the direction of the laser beam to be redirected towards a surface that is not in line-of-sight of the laser beam. A mechanism (not shown) is provided for facilitating and controlling

the redirection of laser transmission end 24 and thus the direction of the laser beam output therethrough.

Fig. 2 shows another configuration of fiber optic beam delivery system 14a. In this configuration, the output of laser unit 16 (from pulsed laser system 12) is coupled into multiple fiber optic cables 18. In this case a higher energy laser unit 16 would be employed, as well as an auxiliary focusing lens 26 for directing the laser energy away from pulsed laser system 12 and into the respective input focusing lenses 20 associated with the plurality of fiber optic cables 18. The use of additional fiber optic cables 18 allows a larger area to be peened for each laser pulse, thus reducing processing time and cost.

The embodiment of Fig. 3 involves coupling multiple pulsed laser units 16 into a single fiber optic cable 18. This configuration increases the peening frequency and decreases processing time. In this configuration a polarizing beam splitter 28 allows multiple beams to be coupled into the same fiber optic cable 18. In this particular embodiment pulse laser units 16 are arranged so as to be approximately orthogonal to each other and to be directed at an angle to a face of polarizing beam splitter 28, as seen from Fig. 3.

Another version couples multiple laser units 16 into multiple fiber optic cables 18. This configuration is shown in Fig 4.

Figs. 5 and 6 illustrate a separate embodiment for laser directing unit 14b. In this embodiment laser directing unit 14b is a telescopic articulated arm mechanism 14b. Telescopic articulated arm mechanism 14b can be designed so as to be controlled robotically and/or manually. The telescopic articulated arm mechanism 14b shown in Figs. 5 and 6 includes laser delivery tubing 30, two mirrors 32, an adjustable telescoping member 34, a prism 36 and a telescoping member focusing lens 38. Laser delivery tubing 30 serves as a channel through which the given laser beam is transmitted. At least two mirrors 32 are mounted within laser delivery tubing 30 for redirection of the laser beam transmitted therein.

Adjustable telescoping member 34 is coupled with laser delivery tubing 30. Adjustable telescoping member 34 is configured for receiving the laser beam therethrough and has a laser transmission opening 40 at the laser transmission end 24 thereof. Due to the adaptable nature of adjustable telescoping member 34, the angular and linear position of laser transmission opening 40 can be selected.

Prism 36 and telescoping member focusing lense 38 are each located in the vicinity of laser transmission opening 40. Specifically, prism 36 is mounted in adjustable telescoping member 34.

Prism 36 is specifically positioned and configured for redirecting the laser beam within adjustable telescoping member 34

outwardly toward and ultimately through laser transmission opening 40. Telescoping member focusing lens 38 is actually located with laser transmission opening 40 and is configured for focusing the laser beam, redirected by prism 36, onto a workpeice surface for laser peening thereof. In this embodiment, as seen in Fig. 6, the workpiece is a blade attachment 42, and the workpeice surface is a dovetail slot thereof. A pair of laser peened patches 46 are indicated upon dovetail slot 44. As can be seen from Fig. 6, these laser peened areas are hidden from a direct line-of-sight.

Telescopic articulated arm mechanism 14b in the embodiment shown in Figs. 5 and 6, is further provided with a robotic unit 48. Robotic unit 48 is configured for translating and rotating adjustable telescoping member 34 in a manner so as to permit selective linear and angular positioning of laser transmission opening 40 and to ultimately allow control of the direction and location of the laser beam transmitted through such opening 40.

As is common practice in laser shock peening, telescopic articulated arm mechanism 14b has an associated water flow 50 for aiding in the control of the laser shock peening process. Such water flow 50 is only schematically indicated, for sake of simplicity, in Fig. 6.

In a method of laser peening a hidden surface of a workpiece, the first step is that of providing a selectively positionable laser

peening apparatus 10 having a laser transmission 24 that is variably and selectively positionable and thereby configured for variably and selectively directing laser energy upon a hidden surface (e.g., dovetail slot 44) of a workpeice (e.g., blade attachment 42). The  
5 next step is to direct the laser transmission end 24 toward the hidden surface that is to be treated, i.e., patch 46 within dovetail slot 44. Laser energy is then delivered, via the laser transmission end 24, upon the hidden surface to thereby initiate laser peening thereof.

10 While this invention has been described as having a preferred design, the present invention can be further modified within the spirit and scope of this disclosure. This application is therefore intended to cover any variations, uses, or adaptations of the invention using its general principles. Further, this application  
15 is intended to cover such departures from the present disclosure as come within known or customary practice in the art to which this invention pertains and which fall within the limits of the appended claims.